

# Advances in the Active Alignment System for the IXO Optics

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## ABSTRACT

The next large x-ray astrophysics mission launched will likely include soft x-ray spectroscopy as a primary capability. A requirement to fulfill the science goals of such a mission is a large-area x-ray telescope focusing sufficient x-ray flux to perform high-resolution spectroscopy with reasonable observing times. The IXO soft x-ray telescope effort in the US is focused on a tightly nested, thin glass, segmented mirror design. Fabrication of the glass segments with the required surface accuracy is a fundamental challenge; equally challenging will be the alignment of the  $\sim 7000$  secondary mirror segments with their corresponding primary mirrors, and co-alignment of the mirror pairs. We have developed a system to perform this alignment using a combination of a coordinate measuring machine (CMM) and a double-pass Hartmann test alignment system. We discuss the technique, its ability to correct low-order mirror errors, and results of a recent pair alignment including progress toward the required alignment accuracy of  $< 2$  arcseconds, and discuss the influence of the alignment process on mirror figure. We then look forward toward its scalability to the task of building the IXO telescope.

**Keywords:** x-ray optics, mirror support systems, optical alignment, Hartmann test, IXO mission

## 1. INTRODUCTION

The success of the Chandra X-ray Observatory has led to the need for a large area x-ray spectroscopy mission. The International X-ray Observatory (IXO) is NASA's next priority in large x-ray astronomy missions. The 2000 Decadal Survey confirmed this, assigning it predecessor, Constellation-X (Con-X)<sup>[1][2]</sup>, the second highest priority for large missions, behind only the James Webb Space Telescope. Con-X was designed to probe questions surrounding black holes and General Relativity, the origin and evolution of the universe, and further the search for dark energy and matter. Indeed, similar fundamental science goals have been the impetus for the Xeus mission proposed at that time by the European Space Agency (ESA) as their next major high-energy astrophysics platform. Common to both missions was a soft x-ray telescope with large collecting area and moderate imaging performance. Recently, NASA and ESA have signed a letter of agreement to pursue a joint mission called the International X-ray Observatory (IXO), merging the science goals and technologies.

IXO contains a single large soft X-ray Telescope (SXT) with a bandwidth of 0.25 to 12 keV, mounted in a single spacecraft and launched on an Atlas 551 or Ariane V. It will provide an effective area that exceeds the fundamental mission requirement of  $3 \text{ m}^2$  at 1.25 keV and  $0.65 \text{ m}^2$  at 6 keV, while maintaining imaging performance of 5 arcsec (2 arcsec goal) for energies less than 7 keV. To accomplish this, two technologies are being pursued to meet the science requirements. The ESA-led technology features stacked, etched silicon "plates" which are formed to provide focusing X-ray optics (described in several other papers in this conference). The NASA effort is a continuation of the Con-X optics development, which has concentrated on the use of thin glass elements, formed by high-temperature slumping on precision mandrels to near-net shape, and then aligning these lightweight elements as pairs and co-

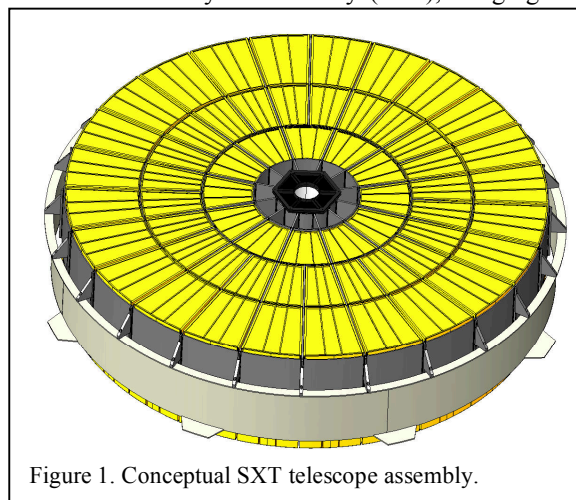


Figure 1. Conceptual SXT telescope assembly.

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aligning the pairs in a modular fashion.

The conceptual SXT mirror assembly is divided into segments, both radially and azimuthally. The current 3.2m diameter SXT design has twelve 30° azimuthal segments in an inner ring, surrounded by middle and outer rings of twenty-four 15° segment modules. With primary and secondary mirror modules containing around 100 thermally formed (“slumped”) mirror segments each, a total of ~14,000 glass segments must be mounted in the SXT with optical precision whilst supported sufficiently well to withstand the rigors of launch.

This module-based approach to supporting mirror segments must allow for precision alignment while maintaining a common focus for all segments, and do so without disturbing the precision optical design of the individual slumped segments. It can be seen in Figure that the modular structure allows for the possibility of holding the segments either on their ends (axially fore and aft) or along their (azimuthal) edges. Both schemes have been used for various mount concepts and alignment approaches. In this paper we describe the development of an alignment technique that constrains the mirror at five points along the fore and aft ends of each segment. During the alignment process, we use both a coordinate measuring machine (CMM) and an optical Hartmann tester called the Centroid Detector Assembly (CDA) to manipulate the constrained points to align the mirror segment. In addition, we present results of a recent alignment of a mirror pair and discuss the progress of the technique toward meeting the mission alignment goals.

## 2. PROCEDURE FOR THE ALIGNMENT OF A MIRROR PAIR

The Constellation-X and now the NASA IXO mission concepts, despite many configuration variations, have consistently included SXTs with thin glass segments<sup>[3]</sup> assembled in a modular structure. Although the exact size and angular span of the modules have gone through several iterations, there have been two fundamental guidelines that derive from the slumping process that have limited the module size and span to a manageable range: (1) Limits on forming mandrel size and the slumping process itself have driven the project toward a consistent segment length of approximately 200mm, and (2) The selected glass (Schott D263) is readily available in sheet widths of 400mm. Various assembly schemes have been proposed that hold the glass on ends or edges whose prime motivation has been alignment of the mirror segments. One of the most enduring concepts consists of formed glass segments are held at a discrete number of points on both the fore and aft ends of each segment, where these points are manipulated precisely to align the mirror segments. In this section, we describe this process and the required hardware to align a pair (primary and secondary reflectors) of Wolter-I optical elements that provides the means to meet all the relevant alignment requirements.

### 2.1 The Process Concept

The process begins with precise knowledge of the shape of the glass segments. Ideally, the segments would conform exactly to the optical prescription for the particular mirror pair being aligned, and one goal of the forming process is to make the segments meet the alignment process requirements. Since the forming process is improving, and the mirror parameters that are the most difficult to measure precisely (average radius, cone angle) are the most critical to the alignment process, we begin by measuring the optics on a metrology mount. To minimize the gravity deflection of the unsupported segment, the measurement is performed with the glass segment vertical. We use a coordinate measuring machine (CMM) to measure and map the optical surface in 3 dimensions. To reduce error and gravity effects, we measure each glass segment with the wide (larger radius) end both at the top and the bottom. Both datasets are input data to “FitCone”, a program developed by Bauer Assoc. to determine the best-fit cone to the surface and its relationship to the mirror edges. The results of the two are averaged and, combining the measurements for both the primary and secondary segments, we determine the best alignment for the pair which also minimizing shape changes, which, if sufficiently large, would require the application of enough force to distort the higher-order shape of the segment.

Once the alignment parameters are determined, the primary mirror is placed in a stiff housing, resting on an adjustable two-point support. Precision adjusters and bonding rails are then affixed to the mirror at the top center point and the three other adjuster positions on the narrow end. The CMM



Figure 2 – Mirror adjusters (top of primary)

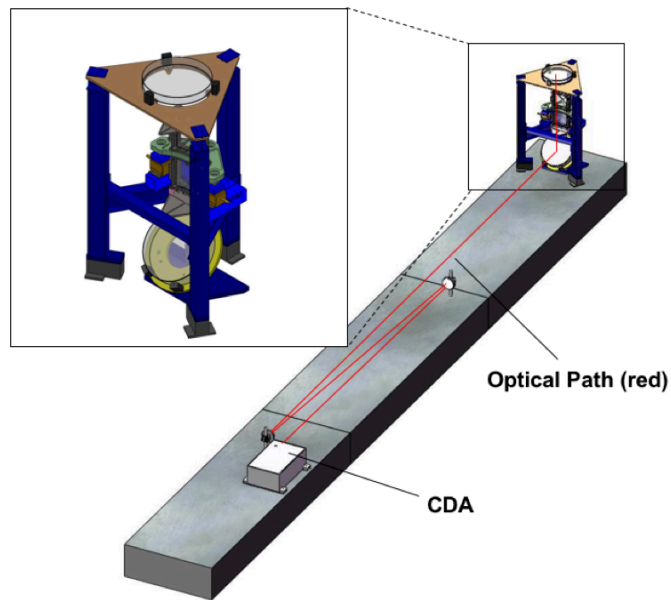


Figure 3. The optical setup of the Centroid Detector Assembly (CDA). Supported by set of optical tables, the system consists of the CDA with a laser source; the beam is folded to produce sufficient focal length and then vertically to pass through the op

is used to adjust the bottom support to correct both pitch and yaw tilts. The three bottom adjusters are then positioned to form the narrow-end radius determined from the alignment optimization, and the wires from the adjusters to the posts are bonded at an intermediate point to provide radial fixity but allow the mirror to move without distorting. The remaining 4 adjusters are then added to the top positions [Fig. 2] and the optimum radius for that end is set (to CMM accuracy).

The entire assembly, with adjusters still attached and holding the wide end of the optic, is bolted to a precision mount and placed in the optical alignment system or Centroid Detector Assembly (CDA) [Fig. 3]. This system is a double-pass Shack-Hartmann test, wherein a laser source, placed at the nominal optic focus, is steered to  $n$  discrete points on the optic surface, passed through an aperture plate to limit beam size, and returned using a precision flat via the same path to a quad-cell detector coincident with the laser source. Based on the position of return spots produced by scanning around the mirror azimuth, the five adjusters are positioned to optimize the mirror alignment (focus and coma) and minimize residuals (higher-order errors). Upon achieving proper alignment with minimum residuals, the five points on the wide end of the primary are bonded to the support rails. The

secondary mirror is then aligned to a separate housing in a similar manner; however, the procedure is modified in that the mirror is held at the top and the top (wide end) radius is adjusted and fixed first, and then adjusters are added to the narrow end and that radius is set on the CMM.

The secondary segment assembly is then bolted to the underside of the precision support plate, using CMM measurements to align the secondary to the primary, principally to make the optical axes of the two segments coincide by adjusting decenter and relative tilt between the pair. The “roughly” aligned mirror pair is then placed in the CDA optical test setup (with the focal length halved due to the introduction of the secondary mirror) and aligned. Rigid body tilt adjustments are performed first, based on deconvolution of the Hartmann spot pattern; this is done to minimize strains on the mirror introduced by adjuster motions. Once minimized, the five actuators are adjusted to minimize remaining tilt errors and reduce the higher-order residual errors. The five points are then bonded in position, producing an aligned and bonded mirror pair. shows an aligned and bonded mirror pair in the CDA optical tower.

### 3. ALIGNMENT RESULTS FOR A REPRESENTATIVE MIRROR PAIR

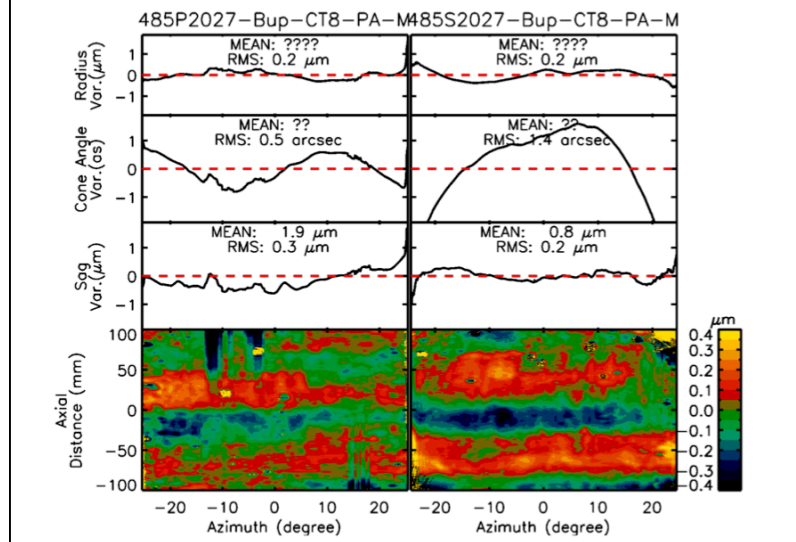
In this section we present alignment results for a specific primary/secondary pair of segments, formed as described earlier by NASA/GSFC. The pair are identified as 485P/S-2027; the first number, 485, refers to the average diameter of the mirror segment, the P/S refers to the primary/secondary segments, and the last (2027) is serialization. The alignment technique is base on work first done at GSFC for a pathfinder assembly (the OAP) and is described in by Reid et al. as the “active alignment system”<sup>[4]</sup>.

#### 3.1 Freestanding mirror measurements

The 485P/S-2027 primary and secondary mirror segments were produced together in a single slumping run, and full segment metrology was performed at GSFC using a Fizeau interferometer and a cylindrical null lens to convert the plane wave to a cylindrical wave<sup>[5]</sup>. These data are shown in Figure 4.

The interferometry data confer that for this mirror pair, if mounted and aligned strain-free, would produce an approximately 14 arcsec HPD in x-ray test, far from the 5 arcsec requirement, primarily due to mandrel figure errors (low- to mid-spatial frequency) and slumping details (mid-spatial frequency); ongoing improvements to this portion of the process are discussed in another paper in this conference. These are generally of higher order than can be measured by the Hartmann test; sag (second-order) and higher-order axial terms are not measurable due to the centroiding of the full-axial-length illumination of the mirror. However, with 14 points measured around the 50° segment, low-order azimuthal variations, especially cone angle variation (second pair of plots) do register in the Hartmann tests. We compute that this mirror pair, mounted strain-free in our test setup, would produce a ~6 arcsec RMS diameter spot (~4 arcsec HPD assuming a Gaussian distribution) due to these errors. **Note: From this point forward in this paper, we will use RMS diameter [RMSD] as the alignment performance metric, since in general the alignment spot distributions are highly non-Gaussian.**

Figure 4. Interferometry data from GSFC freestanding measurement. Note that the mean radius and cone angle, needed values for the alignment process, are not captured. SAO makes these measurements.



As mentioned earlier, the first step in the process is to measure the conic parameters of both mirrors in the free state, to determine an optimal alignment condition, essentially matching radii with minimum strain imparted to either mirror. To obtain the input data, the reflective surface is measured with a 20 point axial (~every 10 mm) by 48 point azimuthal (every degree) grid. The FitCone parameters for the mirrors are given in Table 1. The wide-end down (WED) and narrow-end down (NED) data are averaged, and an optimum set of radii is determined for both segments.

### 3.2 Primary Alignment

The primary mirror is aligned according to the procedure outlined in Section 2.

Figure 5 is a plot of the data for the final CMM measurements of the 2027 primary mirror segment. Measurements at the actuator positions were taken first (red diamonds) to confirm correct adjustment, and then a final scan along the top (red) and bottom (blue) of the segment was made. There are several things to note in these data: (1) The actuator position measurements and the line scan agree to CMM precision at the actuator locations, (2) the sharp dip around +75mm in the bottom scan is an actual “dimple” in the optic at that location, produced during the slumping, and (3) the “tilt” in the bottom scan is due to a lateral offset of the bottom center of curvature, meaning the mirror vertical axis is tilted slightly. Rigid body effects such as this “yaw” tilt can be corrected during optical alignment.

The P mirror in its housing is then taken to the CDA optical alignment system for final alignment. The three

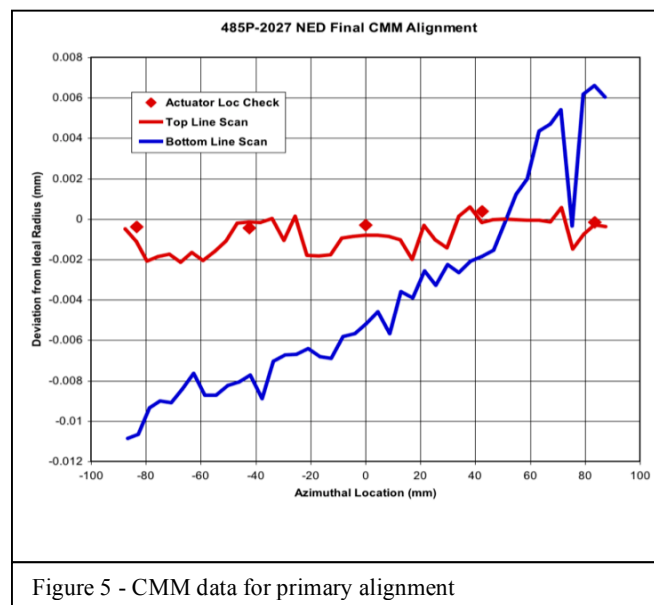


Figure 5 - CMM data for primary alignment

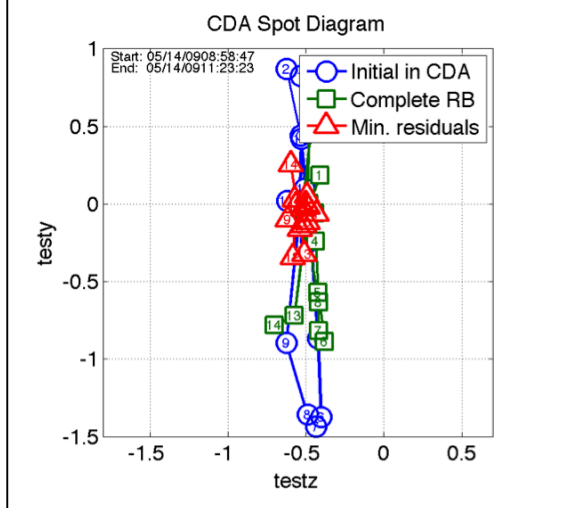


semi-kinematic supports in the tower have vertical adjustment, allowing the entire assembly to be tilted in both axes. This is done to bring the mirror into the best alignment possible without actuator motion. Once the best rigid body alignment has been achieved (based on deconvolution of the Hartmann pattern, see reference [5]), the actuators are used to minimize the spot size. A spot size of approximately 2.4 arcsec RMS diameter was achieved for this primary. Once the best alignment state has been achieved, epoxy used to bond the mirror segment at the adjuster locations to the radial rails.

### 3.3 Mirror Pair Alignment

The procedure to mount the secondary is similar to that for the primary; the fundamental difference is that the top edge is used to support it and the radius is fully set by the CMM (similar to the bottom of the primary), with two fully bonded points and three fixed wires. Actuators are then mounted to all 5 bottom (narrow end) clips and the rough radius of the five points is set using CMM measurement. At this point, however, the procedure diverges. The housing is now mounted to the other side of the plate to which the P housing (with its bonded segment) is mounted. The CMM is then set to reference the P-housing for all measurements of the assembly. The four critical radii (top and bottom of both segments) are then scanned, and the S-housing is aligned in 5 degrees of freedom (all except distance from the P-housing, also known as despace, which is fixed) to place the 4 radii such that the optical axes of the two segments are correctly aligned.

Figure 6. Spot Diagram from CDA alignment of the mirror pair. The blue curve is the initial alignment state; the green curve is after rigid-body adjustments (tilts) were made between the two mirrors; the red curve is the final pair alignment state (3.7 arcsec RMSD).



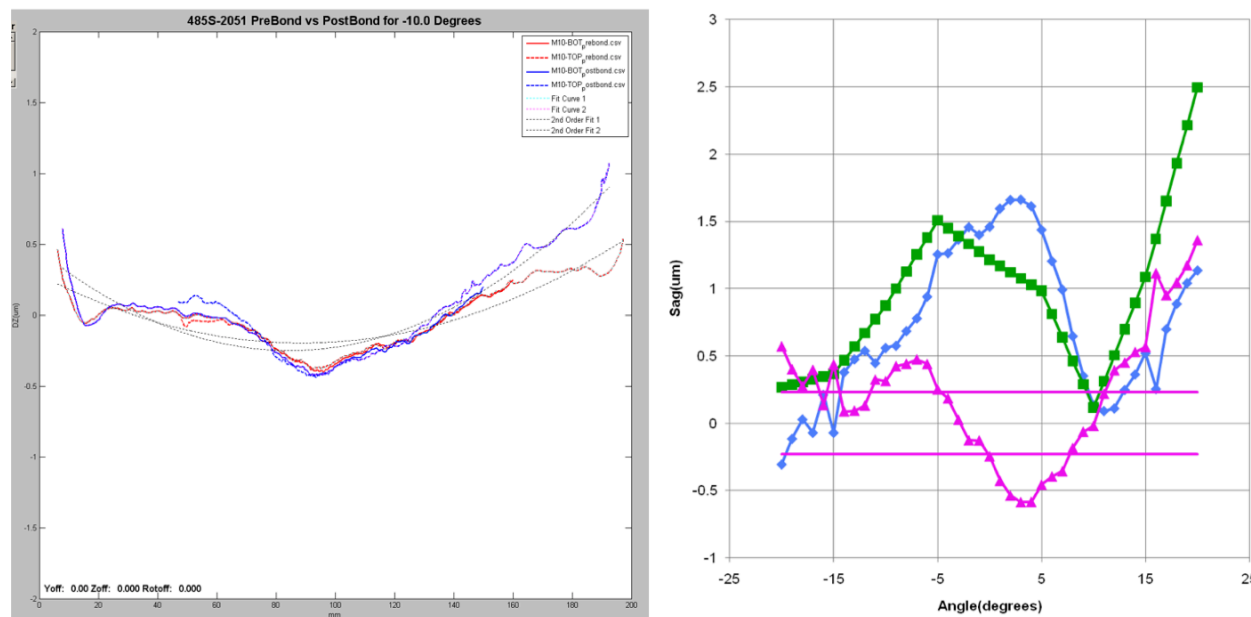
The assembly is then taken to the CDA setup, which has been reset to the focal length appropriate for the mirror pair (8.4m, for these segments) and aligned optically. Since the mirrors are fixed together at the plate, and the optical system is now two-bounce, rigid body alignments are relative (primary to secondary). Initial optical measurements and decomposition into the relative tilts determines whether or not shimming is necessary to achieve a reasonable starting point for fine adjustments with the actuators. If necessary, the pair is removed, shimmed, re-measured in the CMM, and returned to the CDA (done once for this particular pair). Once alignment can be achieved with sufficiently small actuator motions (currently targeted for 25 microns or less, TBR), we perform the actuator adjustments to trim the tilt for the best compromise of one-theta (focal length), two-theta (coma) errors, and higher-order errors to produce the minimum spot size. Figure 6 shows the progression of CDA measurements for the -2027 pair, from more than 25 to less than 4 arcsec RMSD.

In this case, the spot size for the pair is only slightly larger than the result for the P-mirror alone. Indeed, despite relatively large and out-of-phase cone-angle variation errors for this mirror pair that as mentioned earlier would produce an approximately 6 arcsec RMSD spot, we achieved 3.7 arcsec RMSD. Although not fully separable contributors, we estimate that we have (1) achieved pair alignment approaching, if not fully achieving, the 1.5 arcsec RMSD error budget requirement, and (2) reduced low order cone-angle variation errors by roughly half.

## 4. LESSONS LEARNED

The first successful alignment of a mirror pair to near flight tolerances showed that our initial process, where the central edge (narrow end of primary, wide end of secondary) is fully fixed at the five actuator positions, over-constrains the mirror for the final adjustments at the opposite end, compromising mirror figure. We have modified the procedure to provide 2-point support and three points of radial fixity at the 5 positions with significantly more flexibility in mirror motion. The data in Figure 7 show the results with our improved procedures; we have improved the sag change from in excess of 5 microns to approximately 0.5 microns RMS from the pre- to post-bond state. This factor of 10 indicates that the source of the problem is understood, but with an error budget tolerance for this change of 0.05 microns RMS, further improvements are needed.

Figure 7. Interferometer measurements of axial profile before and after alignment and bonding of the secondary mirror. The first plot are the data for a representative scan (+10 degrees); the second is a summary of the derived sag from the 45 scans performed across the mirror azimuthal width. The magenta curve is the pre- to post-bond difference, with the horizontal bars representing the expected measurement error.



With additional care, more measurements, and improved tooling, we expect to be able to align the mirrors with minimal sag change on the next aligned pair. It is also clear that the figure measurement requires improvement; the current technique has a measurement error of about 10 times the sag change requirement.

## 5. CONCLUSIONS AND PLANNED FUTURE WORK

The alignment of thin-glass segments has progressed significantly. We have achieved alignment of a pair that approaches the alignment requirement of less than 2 arcsec RMSD, in a flight-like housing. There are no significant technical hurdles to applying the technique to the hundreds of shells in the flight mirror assembly module. We have shown the process to be largely deterministic, and with this or similar hardware and fairly simple software, the process could be automated, which may be key to producing a realistic schedule for flight mirror production.

We plan to repeat the process with a mirror pair with better free segment errors and using the process improvements described in the previous section. The intent is to show that the process is repeatable, and that the near-flight alignment tolerances can be achieved while maintaining mirror figure. Following that, and depending on progress in mirror production, we hope to receive a pair with much smaller sag and mid-frequency errors, such that an x-ray test could be performed on the aligned pair that would both confirm the alignment result and provide direct x-ray measurement of our progress toward the 5 arcsec HPD mission requirement.

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